



SATELLITE-BASED COMPARATIVE ASSESSMENT OF SHORELINE DYNAMICS USING DIGITAL SHORELINE ANALYSIS SYSTEM (DSAS) IN TERENGGANU AND JOHOR, PENINSULAR MALAYSIA

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ARTICLE INFO	ABSTRACT
Article History: Received: 20 October 2025 Revised: 29 April 2026 Accepted: 14 June 2026 Published: 15 August 2026 Keywords: Shoreline, Landsat satellite data, DSAS, U-Net, LRR, NSM, Terengganu, Johor	The current study aims to analyse long-term coastal processes along the coast of Terengganu and Johor in Peninsular Malaysia over a 34-year period (1990–2024) with the aim of comparing two quite different coastal systems that vary in geomorphological characteristics and level of anthropogenic alteration. The eight years (1990, 1993, 1998, 2002, 2008, 2014, 2018, and 2024) were selected based on cloud-free satellite image availability and spatial consistency. DSAS is used to represent long-term shoreline change. Annual Landsat satellite remote sensing composites were examined and the shoreline was drawn using the U-Net deep learning segmentation model, with an overall accuracy of 98.7%, which provided the most robust shoreline delineations. Digital Shoreline Analysis System (DSAS) was used to measure the shoreline changes by use of Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) measures. The results show that the Terengganu coast is relatively stable and shows a medium erosion and accretion due to the dynamics of the monsoonal waves in combination with the recent introduction of coastal protection structures. Johor coast, on the other hand, shows high rates of accretion due to large-scale land reclamation, estuarine sedimentation, as well as urban development, and erosion persists along the coast facing the Malacca, which experiences high wave energy.

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Introduction

Geomorphological changes are increasing rapidly in the coastal areas of Southeast Asia due to urbanisation, land reclamation, and a change in sediment supply and sea level (Sengupta *et al.*, 2023; Dong *et al.*, 2024; Zhang *et al.*, 2024). According to recent geospatial studies, the shoreline is controlled by the interaction of natural fluid dynamic processes and anthropogenic activities, incorporating tides, wave action, ocean currents, sediment influx, excavation, shoreline engineering, and port-related reconfiguration, focusing on the need for temporal analysis of distinct coastal

settings (Gopinath *et al.*, 2023). The progression of multi-decadal satellite data has transformed the operational process of coastal monitoring by providing a consistent and extensive evaluation of shoreline change that supports the more traditional in-situ and historical measurements (Graffin *et al.*, 2023; Vitousek *et al.*, 2023; Vos *et al.*, 2023; Holzner *et al.*, 2025). The Digital Shoreline Analysis System (DSAS) has become one of the primary tools in the quantification of shoreline change using standardised measures, including Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End-Point

Rate (EPR), and Linear Regression Rate (LRR) (Himmelstoss *et al.*, 2021). These indicators allow predictable and repeatable comparisons of the erosion and accretion patterns, which form a solid foundation for the long-term monitoring and management of the coasts. When multi-decade Landsat data archives are used for DSAS, they evaluate shoreline dynamics exceptionally, by using standardised parameters like NSM, EPR, and LRR to assess erosion and accretion trends at a regional level. It is not exemplary, but these metrics give us a reliable way to track how the shoreline is changing over time (Chettiyam Thodi *et al.*, 2023; Gopinath *et al.*, 2023).

Current developments in Artificial Intelligence (AI) and deep learning have further improved shoreline mapping by making land and water boundaries more precise and automatic in both spectrally complex and anthropogenically altered environments (McAllister *et al.*, 2022; Christofi *et al.*, 2025; Khurram *et al.*, 2025). Conventional index-based methods, including the Normalised Difference Water Index (NDWI) are usually ineffective in turbid or mixed pixels, which leads to the misclassification of land and water boundaries under complicated optical conditions (Ye *et al.*, 2024; Zhao *et al.*, 2025).

Deep-learning models like U-Net and DeepLabV3+ have definite benefits over manual digitisation and threshold-based designs, and are effective at capturing contextual spatial patterns to define the shoreline with a high level of accuracy (Aghdami-Nia *et al.*, 2022). Hybrid CNN transformer models also expand this potential through multi-sensor and multi-temporal data (long-term data) to analyse (Chen *et al.*, 2023; Li *et al.*, 2025; Yang *et al.*, 2025). These AI-driven models, along with DSAS, result in an efficient, scalable workflow of automated shoreline extraction and statistical quantification, which can be useful in the tropical monsoon environment with frequent cloud cover and dynamic coastline processes (Rostami *et al.*, 2023).

On the regional level, the reclamation of land, the destruction of mangroves, and the development of ports have been associated with

significant shoreline migration (Kanniah *et al.*, 2021; Cipriani, 2022; Zulkifle *et al.*, 2024). The progradation was measurable due to large-scale reclamation projects along the western and southern coasts of Malaysia, which interfered with the sediment transportation and intertidal habitat (Chee *et al.*, 2023). Nevertheless, there are limited comparative studies that have concurrently investigated the interactive impacts of natural monsoon-driven processes and human activities on the coastal systems with a contrasting environmental and developmental nature.

The paper integrates the U-Net deep learning model with DSAS to examine shoreline change in Terengganu and Johor (1990–2024) and obtain better spatial accuracy and statistical reliability. The combined methodology offers more information about the coastal processes influenced by natural and human processes. Terengganu is a naturally developing, high-energy monsoonal wave-dominated coast (Ariffin *et al.*, 2018) while Johor is an example of a highly engineered shoreline altered in terms of reclamation and port development (Zulkifle *et al.*, 2024).

This study is important to understand long-term shoreline dynamics over multiple decades by using multi-decade landsat data to assess shoreline physical activities in Terengganu and Johor. This research evaluates shoreline changes between 1990 and 2024, to understand the impacts of geomorphic settings and human activities on the spatial variability on shoreline changes. The novelty of this study is the combination of U-Net deep learning-based shoreline extraction and DSAS based shoreline change analysis for a better regional comparison. This improved shoreline definition supports more consistent extraction, allowing a better understanding of long-term shoreline dynamics in various geomorphological settings.

The results provide valuable insight into the changing environment of Malaysia's coasts and lay the groundwork for developing sustainable, risk-based strategies for the future. These are crucial for building coastal resilience,

particularly in tropical monsoonal regions. Shoreline change history, when integrated with factors such as geomorphological features, slope, tidal range, and wave climate can contribute to comprehensive coastal risk assessment (Naga Kumar *et al.*, 2022).

Materials and Methods

Study Area

The coastline in Peninsular Malaysia is characterised by alternating regimes in monsoons, whereby the northeast monsoons bring in high-energy waves and rainfall, and southwest monsoons bring about smooth periods. The process of seasonal forcing, as well as fluvial sediment delivery and anthropogenic changes (reclamation, urbanisation, mangrove modification), controls the development of shoreline form and dynamics.

The Terengganu Coast (Figure 1) has the length of about 320 km that runs between the latitudes $4^{\circ}30' \text{ N}$ and $5^{\circ}45' \text{ N}$ to the open waters of the South China Sea. High-energy northeast monsoon waves are the most significant feature of the exposed coastline as they form strong longshore drift and periodic beach erosion, constantly redefining its sandy barriers and nearshore morphology (Mohd Akhir *et al.*, 2014; Ariffin *et al.*, 2018). The coast includes barrier dunes, sandy beaches, estuarine inlets, and mangrove fringes along the banks of major river mouths with sediment contribution being mainly caused by the Terengganu, Dungun, and Kemaman Rivers (Mohd Akhir *et al.*, 2014; Ariffin *et al.*, 2018). While the coast is largely natural, the urbanised areas of Kuala Terengganu and Chendering have been altered through seawalls and revetments, which locally break the cycle of sediment retention and affect nearshore processes (Rashidi *et al.*, 2021).

The 400 km long coastline (between $\sim 1^{\circ}20' \text{ N}$ and $2^{\circ}20' \text{ N}$) of Johor (Figure 2) borders the South China Sea to the east and the Singapore Strait to the south, thus, constituting a semi-enclosed marine ecosystem. In the 1990s, its western and southern parts, especially around

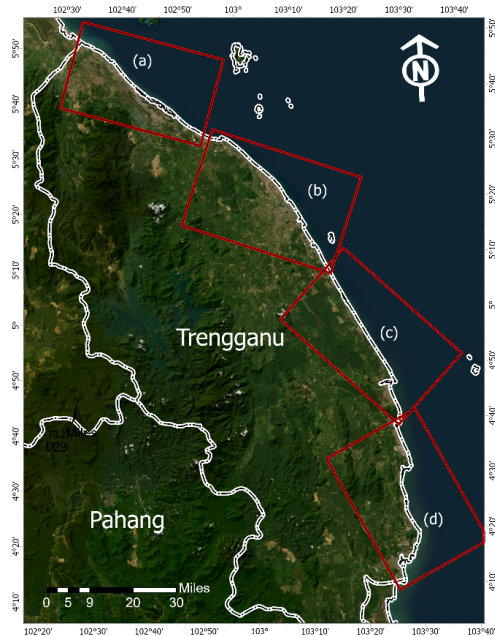


Figure 1: Location map of the Terengganu Coast
Source: Authors

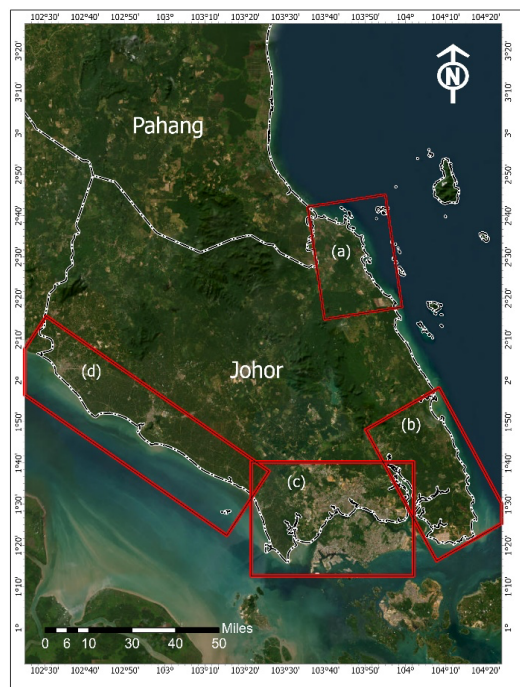


Figure 2: Location map of the Johor Coast
Source: Authors

Johor Bahru, Pasir Gudang, and Tanjung Pelepas, experienced mass reclamation of lands, port development, and armouring of coastlines (Chee *et al.*, 2023; Zulkifle *et al.*, 2024). Such reclamation projects have interfered with natural sediment transportation, produced new littoral basins and shifted tidal exchange patterns (Kanniah *et al.*, 2021). The eastern coast of Johor (between Mersing and Sedili), on the other hand, is more pristine, with mangroves, estuaries, and little engineering work. As a result, Johor is a classic example of a hybrid coastline, where some parts are engineered and some areas have major natural features (Table 1).

Methodology

The Terengganu and Johor coast of Peninsular Malaysia were assessed for the shoreline dynamics using multi-temporal Landsat imagery (1990-2024). The data set consisted of Landsat 4–5 TM, Landsat 7 ETM+, Landsat 8 OLI, and Landsat 9 OLI-2, surface reflectance data

(Level 2) downloaded by Google Earth Engine (GEE) (cloud-free mosaics generated for each year) (Khurram *et al.*, 2024). The eight years (1990, 1993, 1998, 2002, 2008, 2014, 2018, and 2024) were chosen according to the availability of cloud-free and spatial consistency. These selected years gave a good representation of long-term shoreline changes, as DSAS is built to track coastal trends over decades, rather than just short-term seasonal shifts. The use of six Landsat spectral bands (visible, near-infrared, and short-wave infrared) worked well for demarcating land-water boundaries and the data were both atmospherically corrected and radiometrically consistent. Level-2 surface reflectance products were chosen.

The U-net Convolutional Neural Network (CNN) was used to conduct automated shoreline extraction; the model was trained on the 2024 composite and tested against the 2018 to check and confirm that it is transferable across time. The U-Net structure was selected because it

Table 1: Summary of geomorphic and anthropogenic characteristics of the study

Coastal Zone	Dominant Coastal Setting	Main Geomorphic Characteristics	Dominant Forcing/ Processes	Major Anthropogenic Pressures
Terengganu Coast	Open east-facing coast exposed to the South China Sea	Sandy beaches, barrier-dune/beach systems, estuarine inlets, and locally mangrove-fringed river mouths	Strong northeast monsoon wave energy, longshore sediment transport, seasonal beach erosion, and recovery	Localised seawalls, revetments, breakwaters, and urban encroachment near Kuala Terengganu/ Chendering
Johor East Coast	Open to semi-open coast facing the South China Sea	Sandy to estuarine coast with mangroves in sheltered sectors and river-mouth environments	Seasonal wave action and storm influence, estuarine/ tidal interaction, sediment deposition near inlets	Comparatively lower engineering intensity than southern Johor; local coastal development
Johor South/ West Coast	Semi-enclosed strait-facing coast linked to the Singapore/ Straits system	Mangrove-dominated shores, mudflats/estuarine environments, reclaimed and armored waterfronts, port-modified coastlines	Tidal exchange and strait circulation are more important than open-ocean wave forcing; locally altered sediment pathways	Major reclamation, port expansion, industrial/ urban development, shoreline armoring, mangrove fragmentation/ loss

Source: Authors

has high spatial accuracy and has been proven to be reliable in complex coastal conditions (Aghdami-Nia *et al.*, 2022b; Khurram *et al.*, 2025). Shorelines were evaluated in the Digital Shoreline Analysis System (DSAS v5.1) to measure Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), and Linear Regression Rate (LRR). Explicit tidal correction was not applied because shoreline positions were derived from annual median Landsat composites, for which the exact tide stage of each contributing pixel was unknown. Instead, tidal influence was incorporated as a quantified positional uncertainty term within the shoreline error budget. The complete methodology is shown in Figure 3.

U-Net

U-Net is a convolutional encoder-decoder (Figure 4) network that was initially made for medical image segmentation (Ronneberger *et al.*, 2015). It has an architecture that consists of a contracting and expanding path, which captures and recreates spatial context and image details, respectively, with skip connections that combine encoder and decoder properties to maintain the boundary reliability (Aghdami-Nia *et al.*, 2022). U-Net can accurately classify pixels based on limited training data in remote-sensing tasks in the coastal environment, and thus, it can be successfully used in the shoreline delineation of optical and SAR images (Chang *et al.*,

2022). More advanced versions like RDUNet and HEDUnet are further improvements of boundaries depiction based on multi-scale residual blocks and edge-based segmentation (Tseng & Sun, 2022).

U-Net Accuracy

The U-Net model was trained using labelled land–water masks derived from the 2024 Landsat composite, with an 80/20 training–validation split, and evaluated on the 2018 dataset using accuracy, IoU, F1-score, and Dice metrics to ensure robust shoreline delineation performance. U-Net model was evaluated against traditional NDWI-Otsu thresholding and Canny-Otsu edge detection techniques using the 2018 Landsat image. The results demonstrate that U-Net achieved superior performance across multiple evaluation metrics, including overall accuracy (0.987), F1-score (0.986–0.990), Intersection over Union (IoU = 0.973–0.980), and Dice coefficient (0.986–0.990) (Table-2). In comparison, NDWI-Otsu and Canny-Otsu methods showed lower accuracy values of 0.952 and 0.972, respectively. This research demonstrates that the deep learning approach offers more precise and reliable shoreline mapping, especially in complex coastal environments where traditional methods face challenges due to spectral mixing and mixed pixels.

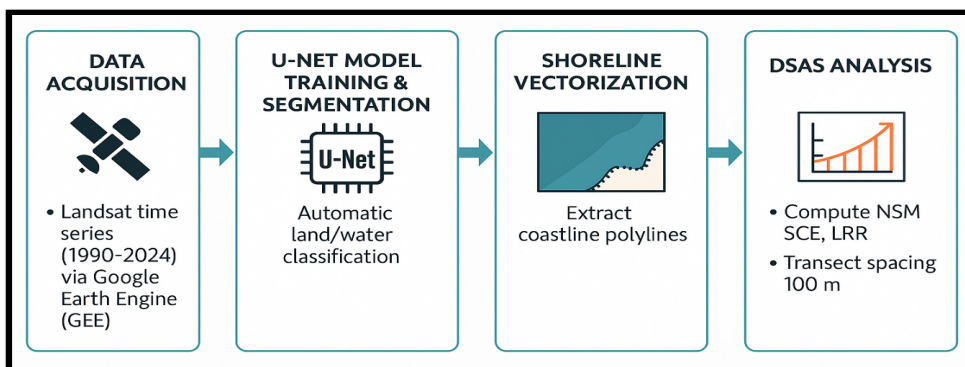


Figure 3: Methodology of the study for shoreline mapping

Source: Authors

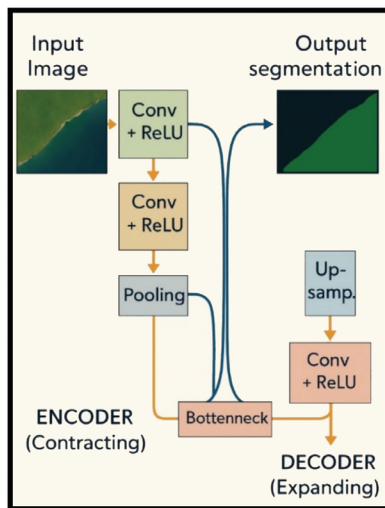


Figure 4: U-Net architecture

Table 2: Performance evaluation of the U-Net model compared with traditional non-deep learning methods using the 2018 Landsat image

Metric	U-Net	NDWI-Otsu	Canny-Otsu
Accuracy	0.987	0.952	0.972
Precision–Land	0.993	0.997	0.997
Precision–Water	0.984	0.963	0.963
Recall–Land	0.987	0.960	0.960
Recall–Water	0.988	0.957	0.957
F1 Score–Land	0.990	0.984	0.984
F1 Score–Water	0.986	0.980	0.980
IoU–Land	0.980	0.958	0.968
IoU–Water	0.973	0.960	0.960
Dice–Land	0.990	0.984	0.984
Dice–Water	0.986	0.980	0.980

Source: Authors

The Digital Shoreline Analysis System

DSAS of shoreline change analysis begins with the creation of a reference baseline, which is typically drawn along the overall trend of the shoreline, and transects are automatically cast at regular intervals and intersect the historical shoreline position (Himmelstoss & Ergul, 2021). DSAS calculates a set of measures of standard metrics along each transect, the SCE, NSM, EPR, and LRR, to measure both the magnitude

and direction of shoreline change through time. These indicators define the maximum level of shoreline movement, the net movement between two temporal endpoints, and the long-term statistical direction of coastal movement.

The EPR approach provides a simple estimate of the shoreline change over the span of two dates as compared to the LRR, which uses various shoreline positions to obtain a rate

estimate that is based on regressions to counter the effect of anomalies and outliers. NSM is used to represent the absolute change in the position of the shoreline between the oldest and latest observations, whereas SCE is used to represent the accumulated envelope of motion regardless of whether the change occurred by erosion or accretion. Statistical confidence intervals are also incorporated in DSAS to describe the uncertainty of every metric, which increases the strength and comparability of the findings.

A combination of these analyses offers a necessary understanding of the stability, variability, and evolution of the coastline, thus, setting up a quantitative basis of erosion risk evaluation, coastal-zone planning, and adaptive management within both naturally dynamic and human-modified coastal systems (Himmelstoss & Ergul, 2021).

DSAS Shoreline Processing Framework

Before running the DSAS analysis, we first converted the U-Net model shorelines to vector data and then reprojected them to the Kertau_RSO_Malaya_analyzes coordinate system for spatial alignment. A baseline was manually set about 1 km offshore, following the general direction of the coastline. This baseline was placed far enough from the shoreline so that we could properly intersect the shoreline positions from different years. We then created transects

perpendicular to the shoreline at regular intervals of 100 m to calculate shoreline change statistics, like Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), and Linear Regression Rate (LRR). Having the same baseline for every year ensured that the measurements were consistent over time. Since DSAS calculates shoreline change along multiple transects, instead of just repeating a single measurement, we did not include traditional error bars. Instead, positional uncertainty related to image resolution and shoreline delineation was considered as part of the shoreline interpretation.

Uncertainty in Shorelines

The shoreline positional uncertainty was estimated using a conservative error-budget approach, which takes into account three key sources of error: Digitizing (E_p), georeferencing (E_g), and tidal stage variation (E_{tide}). Since the shorelines were based on annual median composites, the exact acquisition time and tidal stage for each pixel could not be pinpointed, making precise tidal normalisation difficult. To account for this, a tidal range of 2 m was assumed, and a foreshore slope of 0.02 was applied, which led to an estimated tidal offset of about 100 m. This approach helps address the uncertainty introduced by tidal influences, offering a more accurate understanding of shoreline positional accuracy (Table 3).

Table 3: The positional uncertainties for shorelines from 1990 to 2024 were calculated using a conservative error-budget approach

Year	Georeferencing Error (E_g) (m)	Pixel Error (E_p) (m)	Tidal Error (E_{tide}) (m)	Total Uncertainty (U) (m)
1990	50	15	100	112.81
1993	50	15	100	112.81
1998	50	15	100	112.81
2002	50	15	100	112.81
2008	50	15	100	112.81
2014	12	15	100	101.83
2018	12	15	100	101.83
2024	12	15	100	101.83

Source: Authors

Results

Digital Shoreline Analysis System (DSAS) evaluation of multi-temporal shoreline between 1990 and 2024 reveals that the shoreline morphodynamics across the Johor and Terengganu coastline are subjected to a divergent set of morphodynamic regimes, which are created by varying levels of natural forcing and anthropogenic alterations. The shoreline is highly spatially variable and morphologically adjusted in Johor, whereas Terengganu is relatively stable, with the seasonally balanced nature of accretion.

Each map (Figures 6, 7, 8, 9) employs a classified colour symbology to represent both the magnitude and direction of shoreline change. For both NSM and LRR maps, warm colours (red, orange, and yellow) indicate erosion (negative values) while cool colours (light blue to dark blue) represent accretion (positive values). Specifically, red denotes the highest erosion and dark blue signifies the highest accretion. The grey colour is used to mark shoreline sections that showed little movement over the study period, reflecting areas of relative stability. This subtle shade helps differentiate these stable zones from those that underwent more significant changes. In this context, SCE and NSM were used to measure the distance and overall movement of the shoreline while LRR was employed to quantify the rate of change at each transect.

Since LRR is based on a least-squares regression fitted to all shoreline positions from 1990 to 2024, it provides a more reliable picture of the long-term shoreline trend. Therefore, the reported patterns of erosion, accretion, and stability are not only descriptive, but are grounded in statistically derived shoreline behaviour while the maps help show how these trends are distributed spatially along the coast. The colour gradient also helps in showing not just the magnitude of change, but also the variation in coastal dynamics across different shoreline segments in each state. The percentages of erosion, accretion, and stability were calculated by grouping the transects into three categories

based on DSAS outputs: Erosion ($< -0.5 \text{ m yr}^{-1}$ for LRR; $< -15 \text{ m}$ for NSM), stable (-0.5 to 0.5 m yr^{-1} for LRR; approximately -15 to 15 m for NSM), and accretion ($> 0.5 \text{ m yr}^{-1}$ for LRR; $> 15 \text{ m}$ for NSM).

Johor has an average Net Shoreline Movement (NSM) of $+66.4 \text{ m}$ and an overall progradation of $+1,917 \text{ m}$ as compared to $+31 \text{ m}$ and $+1,183 \text{ m}$ of Terengganu. Similar Linear Regression rate (LRR) results indicate 41% accretion and 20.5% erosion in Johor and 32% and 13% in Terengganu, with the latter having a higher percentage of stable transects (55%). This difference is further enhanced by the mean accretion and erosion rates, which are $+1.92 \text{ m yr}^{-1}$ and -0.52 m yr^{-1} , respectively, in Johor and Terengganu (Table 4). These values indicate the increased sensitivity of Johor to the short-term disturbances and structural interventions, in contrast to the feedback profile of Terengganu based on the natural redistribution of sediments.

The morphodynamic complexity in Johor is due to the intensive reclamation, dredging, and port construction, which interfere with littoral transport and form alternating erosion-accretion cells. The northern and northeast sectors (between Mersing and the Johor River delta) show high progradation based on estuarine sedimentation and reclamation, but the central and southern ones are highly subject to local erosion near the engineered shoreline. These trends highlight a disaggregated sediment regime, in which local accretion tends to mask downstream shortages, which argues the need to employ comprehensive sediment-management approaches to maintain littoral continuity and reduce imbalance.

On the other hand, the coast of Terengganu has stable accretion, but the spatial gradient is at a minimum. Most transects record positive values of LRR of $+3$ – 10 m yr^{-1} around Setiu and Kuala Terengganu, which can be credited to riverine sediment transfer and embayments. Localised erosion -3 to -8 m yr^{-1} localised erosion takes place around headlands and revetments, especially in and around Kuala/Nerus and

Marang, which are site-specific structural effects as opposed to system-scale retreat. NSM results deny cumulative progress of +100–400 m to the north and the middle of the reach balanced by slight erosion in the south (-50 to -200 m). The east coast of Terengganu exhibits a general natural resilience, as disrupted by the re-deposition of monsoonal processes and fluvials in the long run, long-term equilibrium is sustained. Conversely, the shoreline of Johor is a classic example of an anthropogenically changed system that necessitates the implementation of a set of sediment-related management measures that can ensure morphological stability to prevent cumulative degradation.

Figure 5 provides the box plots that display the distribution of SCE, NSM, EPR, and LRR. In each box, an Interquartile Range (IQR) is shown and the median values are represented by the red lines. Johor shows a very high variability and the frequency of outliers, which are anthropogenic changes like land reclamation and port development. Conversely,

Terengganu has steadier, naturally controlled shoreline dynamics that are mostly caused by the monsoons.

The LRR and NSM along the Johor coastline are shown in Figures 6 and 7 together; it demonstrates the space possession and strength of the shoreline change of the Johor coast using the DSAS Linear Regression Rate (LRR) analysis. The sea-coast is separated into four morphodynamic zones (a, b, c, and d) encompassing the different erosion and deposition behaviour in the 1990–2024 period. The coloured transects distinctly characterise the different reactions of the coastal areas, the presence of green colours characterising the accreting parts whereas red colours characterise the erosion. The high accretion is focused on the northern and northeastern coast (zones a and b), whereby the estuarine sedimentation and creation of land have facilitated extensive shoreline growth. However, in contrast, the zones c and d comprising the central coastline and southern coastal regions, show alternating

Table 4: Summary of DSAS metrics statistics

Descriptive Statistics	Johor	Terengganu
Total number of transects	5391	2435
Mean Shoreline Change Envelope (SCE)	103.4	60.12749487
Maximum Shoreline Change Envelope (SCE)	1926	1197.2
Minimum Shoreline Change Envelope (SCE)	0.9	0.45
Percentage of transects exhibiting erosion (LRR)	20.5	12.89
Percentage of transects exhibiting accretion (LRR)	41	32.07
Percentage of stable transects (LRR)	38.5	55.03
Maximum erosion (NSM based) (m)	-341.4	-364
Mean erosion (NSM based) (m)	-17	-8.33
Maximum accretion (NSM-based) (m)	1917	1182.94
Mean accretion (NSM based) (m)	66.4	30.95
Percentage of transects exhibiting erosion (NSM)	20.7	14.086
Percentage of transects exhibiting accretion (NSM)	44	33.75
Percentage of stable transects (NSM)	35.3	52.15
Mean erosion rate (m/year)	-0.52	-0.25
Mean accretion rate (m/year)	1.92	0.98

Source: Authors

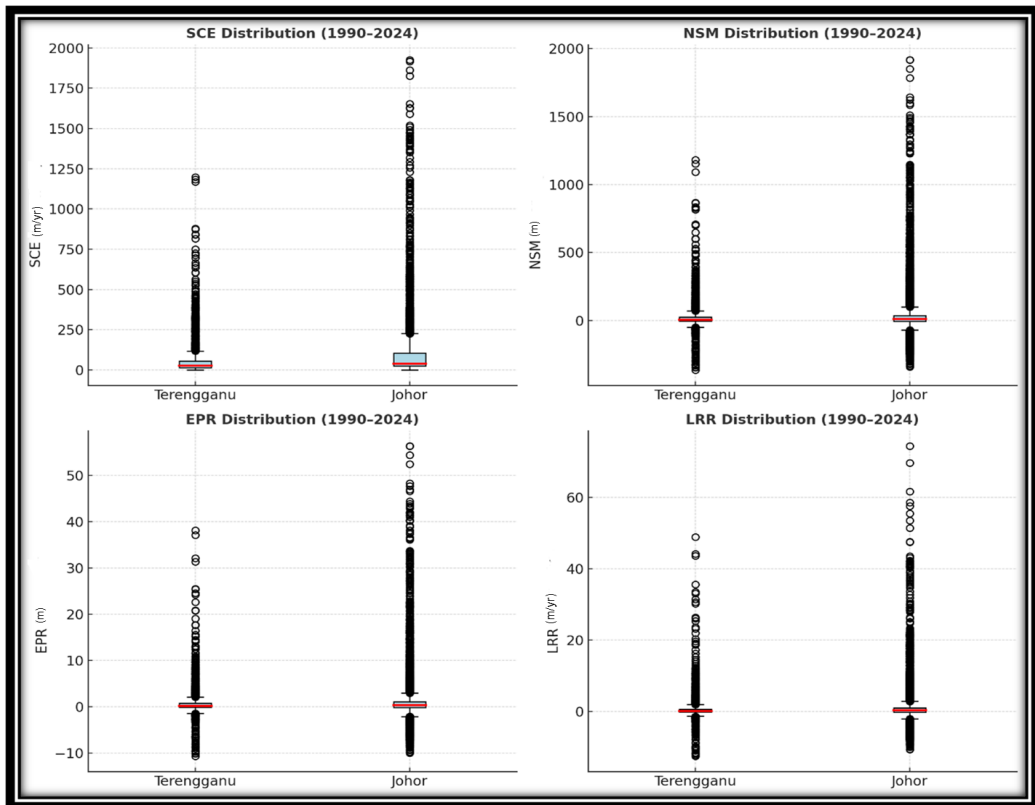


Figure 5: Box plot comparison of shoreline changes indicators for Terengganu and Johor (1990–2024)
Source: Authors

erosion and accretion stripes that relate to the reclamation fronts, dredging processes, and port construction, especially along Tanjung Pelepas and Johor Bahru. Each sector is accompanied by bar graphs that highlight the amplitude and frequency of change. Both localised erosional peaks to the order of -10 m yr^{-1} and accretional peaks to the order of $+70 \text{ m yr}^{-1}$ indicate the fragmented character of littoral transport under severe human modification. These geometrical imbalances show that the shoreline of Johor is not controlled by continuous sedimentary activities but instead by discontinuous human activities that lead to patchy progradation and downstream sediment deficiency. Generally, the figure represents the visualisation of Johor as an extremely fast-moving and artificial coastal system, with intensive reclamation and port development having reorganised natural

sediment pathways, constructing a mosaic of accretion and erosional segments, which together define the morphodynamic regime at Johor.

Figures 6 and 7 present the LRR and NSM for the Terengganu coastline, illustrating its predominantly stable to moderately accretional nature. The maps and transect plots show four coastal zones, a, b, c, and d, each depicting subtle variations in erosion and deposition. The northern and central sectors (zones a and b) display consistent accretion, with LRR values typically ranging from $+3$ to $+10 \text{ m yr}^{-1}$ and NSM advances up to $+400 \text{ m}$, supported by riverine sediment supply and monsoon-driven redistribution. In contrast, southern zones (c–d) exhibit isolated erosion pockets ($\text{LRR} \approx -3$ to -8 m yr^{-1} ; $\text{NSM} \approx -50$ to -200 m) near Kuala

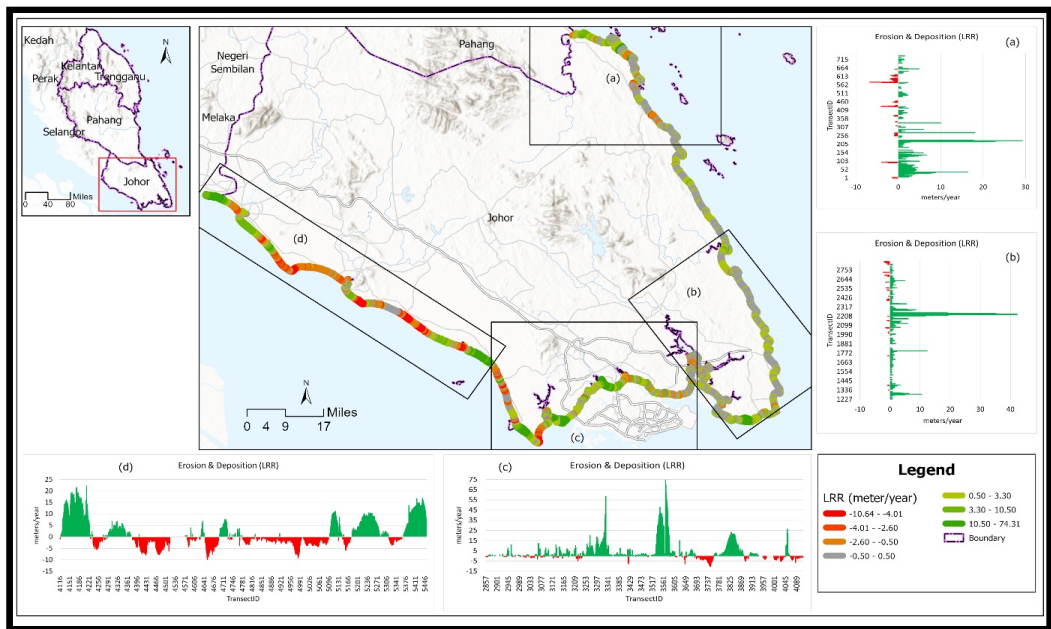


Figure 6: Spatial and temporal variability in Linear Regression Rate (LRR) along the Johor Coast (1990–2024) derived from DSAS analysis
Source: Authors

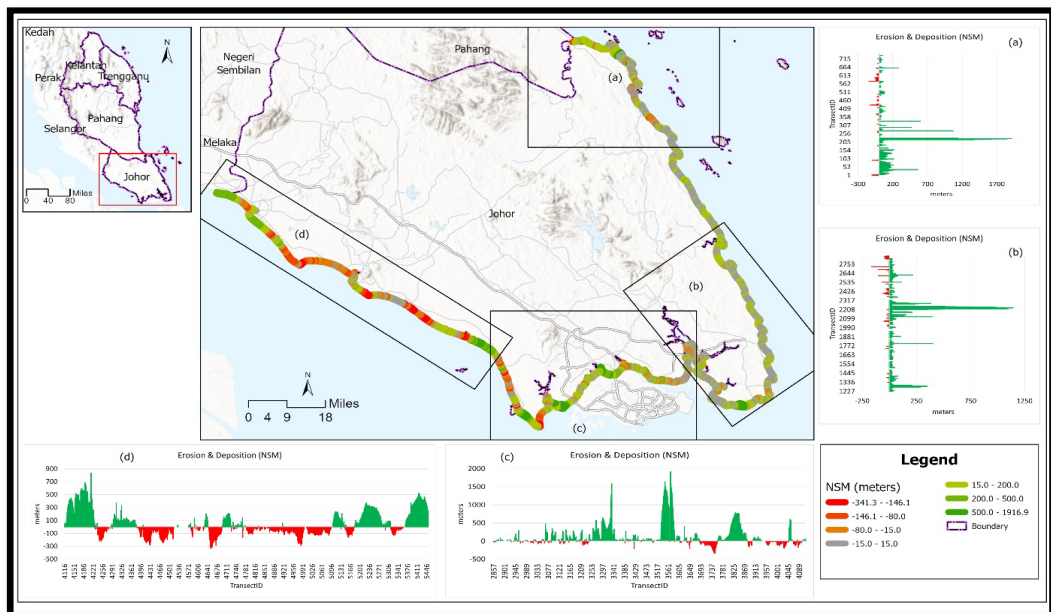


Figure 7: Spatial and zonal variability of Net Shoreline Movement (NSM) along the Johor Coast (1990–2024) derived from DSAS analysis
Source: Authors

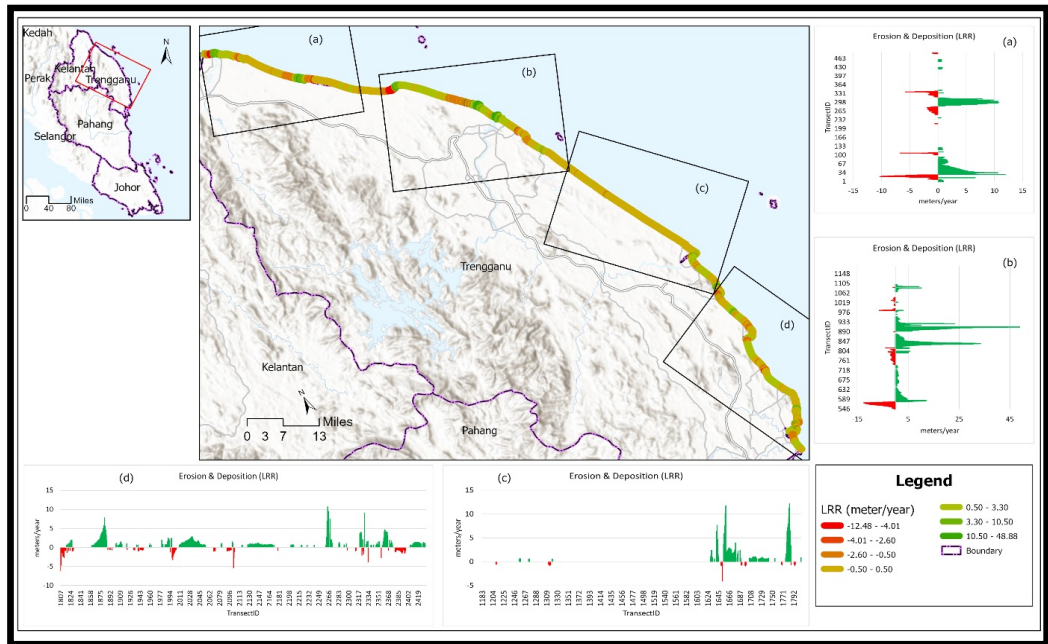


Figure 8: Spatial and temporal variability in Linear Regression Rate (LRR) along the Terengganu Coast (1990–2024) derived from DSAS analysis
Source: Authors

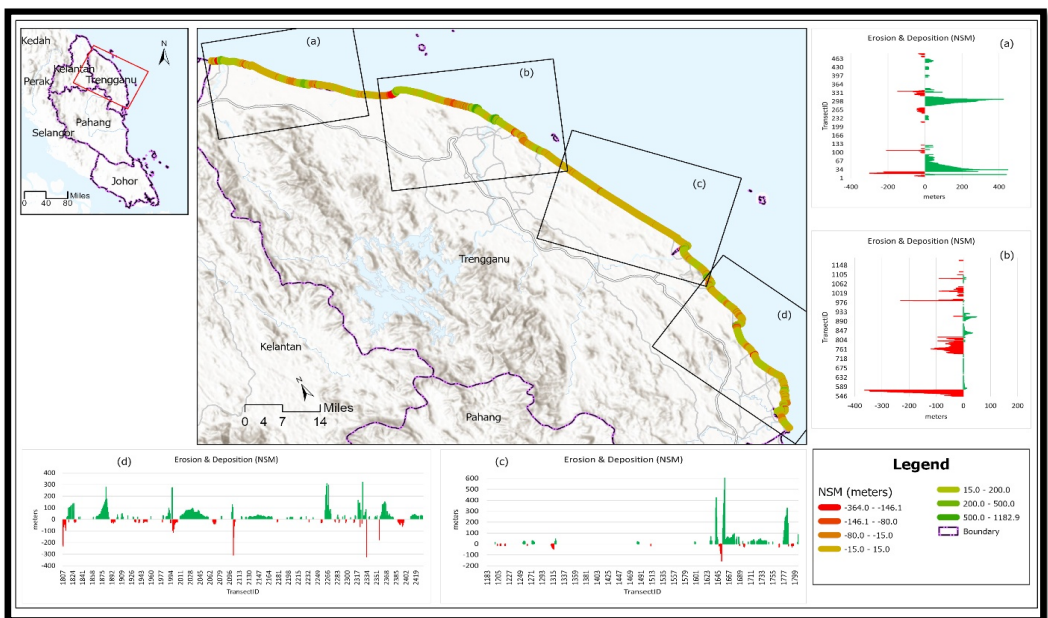


Figure 9: Spatial and zonal variability of Net Shoreline Movement (NSM) along the Terengganu Coast (1990–2024) derived from DSAS analysis
Source: Authors

Nerus and Marang, linked to local revetments and coastal defence structures.

In general, the two illustrations demonstrated an erosion-resistant and naturally balanced shoreline, in which intermittent erosion is compensated by seasonal sediment redeposition to ensure the long-term stability of the coast in Terengganu on the east coast of the country.

Process Controls and Adaptive Capacity

The development of the shoreline is strictly controlled by monsoonal processes in Terengganu, where the sediment is mobilised in the northeast monsoon and deposited in the southwest monsoon in a cyclic manner. The net accretion and shoreline balance is maintained through this seasonal interaction as opposed to the more anthropogenically influenced, directional development of Johor. The low beach slopes, lagoons behind the bars, and mangrove strips are the features of the coast that increase its resilience as they absorb the energy of the waves and stabilise the exchange of sediments. Nevertheless, localisability of sensitivity to storm surges and to modified flow regimes is evident in isolated transects around engineered defences, which suggests future weaknesses in the event of rising sea levels.

Synthesis and Strategic Insights

An overview of the coastline in Johor and Terengganu points to two different ways of coastal development: The morphology of Johor is anthropogenically altered and spatially fragmented, and the territory of Terengganu is naturally controlled and process-based. In this regard, Johor needs active, location-specific interventions to consider the interrupted sediment pathways, and Terengganu can utilise the preventive and monitoring-based strategy to achieve its balance. Finally, the satellite-DSAS framework is used to measure the change and diagnose the emergent risk areas, plan the sediment corridors, and inform predictive adaptation strategies to ensure sustainable coastal resilience.

Discussion

The present findings support the initial hypothesis that shoreline behaviour in Johor and Terengganu is fundamentally divergent, and that this contrast is largely controlled by differences in geomorphic setting and the degree of anthropogenic disturbance. In Terengganu, the predominance of positive LRR and NSM values across most transects points to a generally accretional tendency, which is consistent with seasonal sediment redistribution and the persistence of a relatively stable morphodynamic regime.

In contrast, the Johor coastline exhibits marked spatial irregularity, with alternating sectors of erosion and accretion that correspond closely to areas influenced by land reclamation, harbour infrastructure, estuarine modification, and shoreline engineering. Rather than indicating a uniform coastal response, this pattern suggests that shoreline adjustment is highly localised and strongly conditioned by human intervention superimposed on natural coastal processes. These results, therefore, confirm, rather than refute, the study hypothesis are consistent with regional evidence from Southeast Asia showing that anthropogenic activity can intensify or redirect natural shoreline variability (Ariffin, 2017; Khurram *et al.*, 2025).

Beyond confirming the contrast between the two coastal settings, the findings also contribute to the broader understanding of shoreline morphodynamics in humid tropical environments. The comparison shows that shoreline change is not a simple linear process, but a spatially uneven and temporally dynamic response to the interaction of monsoonal forcing, sediment supply, coastal configuration, and human modification of sediment pathways. This is particularly evident in Johor, where engineered interventions appear to disrupt littoral processes and create alternating cells of erosion and deposition, rather than a continuous trend of shoreline advance or retreat. The Terengganu coast, by comparison, appears to retain a stronger connection to natural sediment exchange processes, although this does not

imply immunity from future destabilisation. In this sense, the study adds to ongoing discussions in coastal geomorphology by showing that shoreline mobility in tropical and estuarine systems must be interpreted within both environmental and infrastructural contexts. The present results align with previous work showing that jetties, breakwaters, reclamation, and industrial development can significantly alter local sediment transport and generate discontinuous coastal responses instead of smooth shoreline translation (Gopinath *et al.*, 2023b).

From a methodological perspective, the study demonstrates the value of integrating deep-learning-based shoreline extraction with DSAS for multi-decadal coastal monitoring. The use of U-Net for shoreline delineation improved spatial consistency and reduced the level of subjectivity typically associated with manual digitisation while DSAS provided a structured means of quantifying shoreline movement through LRR and NSM metrics. This combination is important because it links recent advances in automated image interpretation with established shoreline change analysis methods, thereby offering a practical framework for regional-scale assessments (Smith, 2023; Zhang *et al.*, 2024).

The significance of this contribution lies not only in the analytical results, but also in the operational potential of the workflow. Because the approach relies on freely available Landsat imagery and cloud-based processing in Google Earth Engine, it remains reproducible and scalable for long-term coastal monitoring. The patch-based application of U-Net further reduces computational demand while the resulting shoreline products are directly compatible with GIS platforms such as ArcGIS and QGIS. This enhances the applied relevance of the work and supports its novelty as a transferable framework for shoreline assessment in data-constrained coastal regions.

At the same time, the study also highlights several difficulties and design-related challenges that must be acknowledged when interpreting

the results. Shoreline position derived from satellite imagery is inherently affected by tidal stage, wave run-up, image resolution, and temporal inconsistency in image availability, including limitations associated with Landsat 7 SLC-off data. These factors introduce positional uncertainty that cannot be fully eliminated, even when the classification performance of the shoreline extraction model is strong.

In addition, the study was designed primarily to detect and quantify shoreline movement, not to resolve the full physical mechanisms underlying that movement. Processes such as nearshore bathymetric change, sediment budget variability, and alongshore transport gradients were not directly quantified, which limits the capacity of the analysis to establish process-based causation. For this reason, the DSAS outputs should be interpreted as diagnostic indicators of shoreline change rather than as fully mechanistic predictors, especially under non-stationary climatic conditions and rising sea levels.

A further limitation is that anthropogenic influence was interpreted from spatial correspondence with observed shoreline patterns rather than through formal attribution using independent temporal datasets. While this interpretation is reasonable and supported by the spatial pattern of results, it remains an inference that should be tested more rigorously in future studies. These limitations do not diminish the value of the present work, but instead define the next stage of research needed to strengthen shoreline change attribution and prediction. Future studies should integrate hydrodynamic modelling, higher-resolution optical datasets, UAV observations, infrastructure time-series mapping, and independent records of reclamation, port expansion, and land-use change to better separate natural and human drivers of shoreline response. Such extensions would allow stronger causal interpretation and improve predictive capacity under future coastal development and climate scenarios.

The management implications are already clear. Johor requires targeted sediment

management strategies, tighter control of reclamation and shoreline engineering, and greater attention to downstream erosion effects created by coastal infrastructure. Terengganu, in contrast, would benefit from protecting natural sediment pathways and avoiding excessive structural intervention that could destabilise an otherwise more balanced coastal system. In this respect, the study fits well within current debates in coastal science and management by showing that effective shoreline assessment must move beyond simple rates of change and instead account for the combined influence of geomorphology, hydrodynamics, and human pressure. The novelty of the work lies in demonstrating this contrast through a reproducible deep learning and DSAS framework while also situating the results within the wider regional discussion on how tropical shorelines are being reshaped by both climate-related forcing and coastal development.

Conclusions

This study demonstrated that shoreline change along the eastern and southern coasts of Peninsular Malaysia is shaped by a complex interaction between natural coastal processes and anthropogenic drivers, with clear contrasts observed between Terengganu and Johor. By integrating deep learning-based shoreline extraction using U-Net with DSAS-based statistical analysis, the work provided an efficient, scalable, and more spatially consistent framework for detecting and evaluating multi-decadal shoreline change.

The findings showed that Terengganu reflects a comparatively more natural sedimentary response. In contrast, Johor exhibits more spatially irregular shoreline behaviour linked to stronger human intervention, highlighting that shoreline management cannot rely on generalised solutions. In this wider context, the study emphasises the importance of localised coastal protection and sediment management strategies that can respond to different geomorphic and developmental settings, particularly in tropical monsoon regions, where

environmental pressures and infrastructure expansion often occur simultaneously. The study also shows the practical value of combining automated shoreline mapping with long-term change analysis to support more reproducible and transferable coastal monitoring. Future research can build on this work by improving the integration of shoreline extraction with dynamic climate, hydrodynamic, and infrastructure data, and by developing accessible open-source tools that can help strengthen long-term prediction, support sustainable coastal policy, and advance shoreline monitoring across regions facing similar environmental and development challenges.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Author Contributions Statement

SK conceptualised the study, performed shoreline extraction and DSAS-based analysis, and prepared the manuscript draft. ABP supervised the work, refined the methodology, and revised the manuscript. MB assisted in GIS analysis and data validation. EHA contributed to geomorphological interpretation. MFA provided insights on oceanographic and monsoonal influences. SBH supported coastal management interpretation and final editing. All authors approved the final manuscript.

Ethical Conduct

There is no need ethical statement for this research paper.

Data Availability Statement

Data are available from the corresponding author on reasonable request.

Declaration of AI-usage

In preparing this manuscript, the authors employed AI-assisted tools to enhance grammar, language, and clarity. All outputs were carefully reviewed and edited by the authors, who accept full responsibility for the accuracy, integrity, and originality of the work.

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